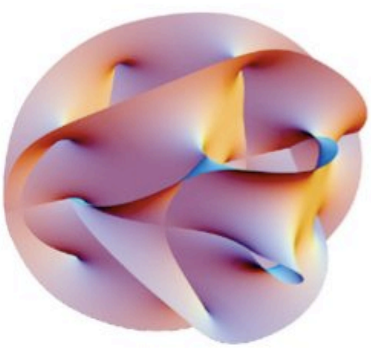
The String Axiverse

Sergei Dubovsky
Stanford U.

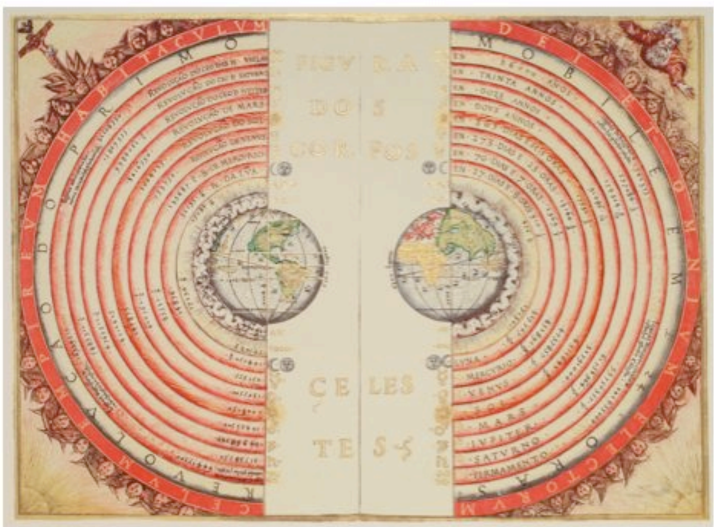


with Mina Arvanitaki, Nathaniel Craig, Savas Dimopoulos, John March-Russel, and Nemanja Kaloper
arXiv:0905.4720, 0909.5440 and work in progress...

String Multiverse:

Plenitude ('$\sim 10^{500}$') of vacua

For the solar system

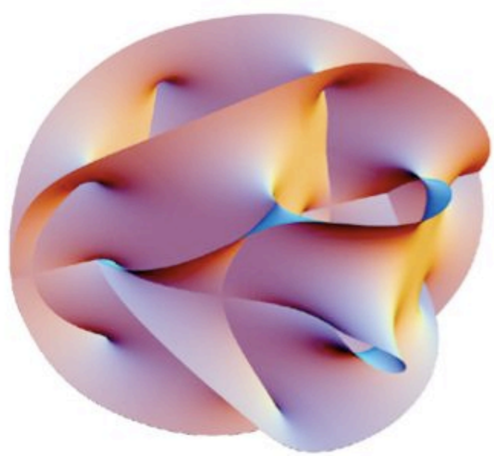


Changes the way we think about our own solar system

Plenitude of solar systems points to anthropic reasoning

Some people got fired for these ideas

MULTIVERSE= Xdimensions + Complicated Topology + Gauge Fields



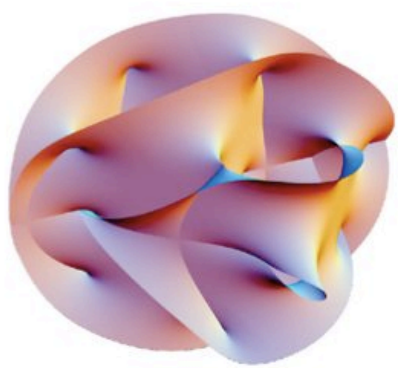
The same ingredients may give rise to

String Axiverse:

Plenitude (10s-100s) of axions in our vacuum

String Photiverse:

Plenitude (10s-100s) of photons/photini in our vacuum



Non-trivial gauge configurations

Solenoid

The Aharonov-Bohm Effect

Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

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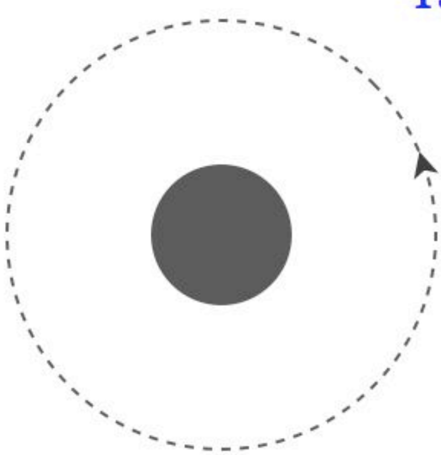

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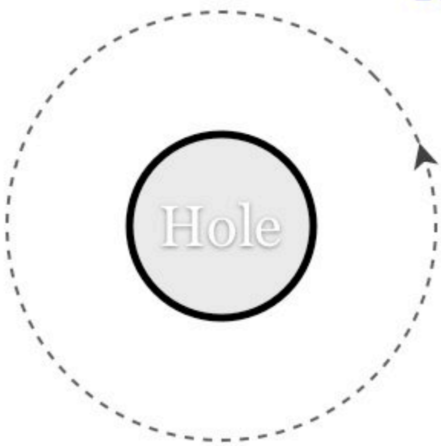

$$e\int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

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Non-trivial topology:
“Blocking out” the core still leaves a non-trivial gauge, but no mass

Acquires an exponentially small mass from a virtual electron going around

Plenitude of Axions

relevant phenomenological parameters: m f_a

$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - m^2 f_a^2 U(a/f_a)$$

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$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - m^2 f_a^2 U(a/f_a)$$

$$m^2 f_a^2 = \mu_{UV}^4 e^{-S}$$

in explicit examples one often finds: $\boxed{f_a \sim \frac{M_{Pl}}{S}}$

What are the 'typical' values of S ?

Axions can be further lifted by fluxes and branes.
How many of them survive?

The key: THE STRONG CP PROBLEM

$$S_\theta = \frac{\theta}{32\pi^2}\int d^4x\,\epsilon^{\mu\nu\lambda\rho}\mathrm{Tr}\,G_{\mu\nu}G_{\lambda\rho}$$

Neutron e.d.m.

$$\bar{\theta} = \theta + \arg\det m_q \lesssim 10^{-10}$$

- Like CC and EW hierarchy problems a precise cancelation of apparently unrelated quantities is required
- NO anthropic reason

A clear call for a new dynamics

The QCD axion

$$S_a = \int d^4x \left(\frac{1}{2}(\partial_\mu a)^2 + \frac{a}{32\pi^2 f_a} \epsilon^{\mu\nu\lambda\rho} \mathrm{Tr}\, G_{\mu\nu} G_{\lambda\rho} \right)$$

Non-pert QCD gives potential $V(a)$ of height $\Lambda_{QCD}^4 = \mu^4 \exp(-8\pi/\alpha_s(\mu))$

$\Longrightarrow$ Axion is a pseudo-Nambu-Goldstone boson

$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim 6 \times 10^{-10} \mathrm{eV} \left(\frac{10^{16} \mathrm{GeV}}{f_a} \right)$$

Minimum of potential leads to axion vev such that

$$\theta_{eff} \equiv \frac{\langle a(x) \rangle}{f_a} + \bar{\theta} = 0$$

solves strong CP!

String theory does NOT predict the QCD axion

- light axions can be removed from the spectrum by orientifold planes, fluxes, branes
- non-perturbative effects may generate contributions to the potential $> 10^{-10} \times$ QCD

QCD axion is a constraint on string model building

and

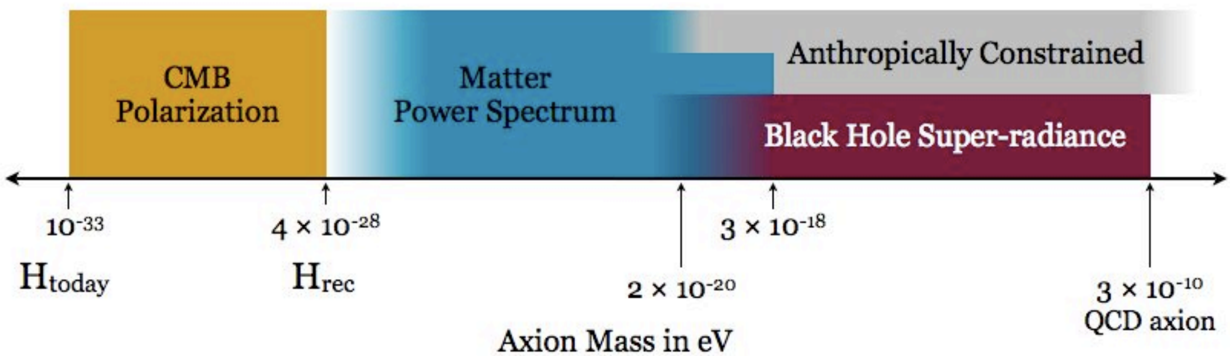
should not be exceptional

(because there is no anthropic explanation for its properties)

Taking seriously the QCD axion and string theory one expects

AXIVERSE=a plenitude of light axions

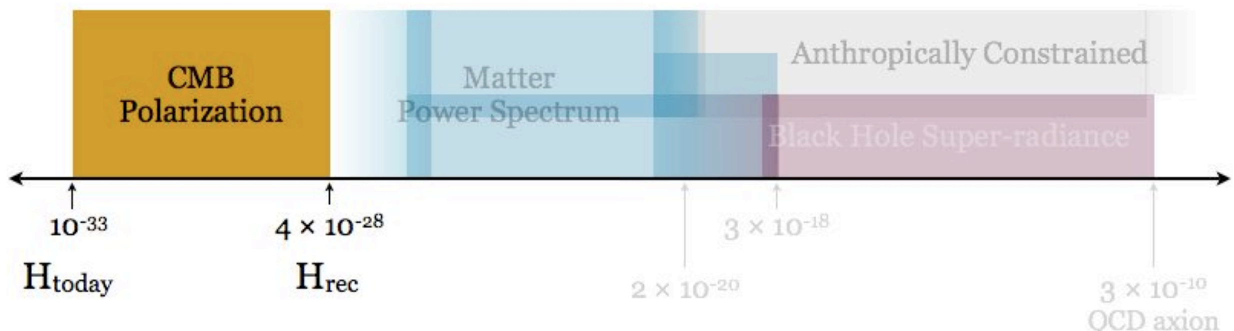
$f_a \sim M_{GUT}$ m: homogeneously distributed over log(energy)



Astrophysical signatures over 23 orders of magnitude

for simplicity assume in the following

$H_{inf} \sim 0.1$ GeV $\quad T_{rh} \sim 10^7$ GeV



coupling to photon: $$\mathcal{L}_\gamma = \frac{C\alpha}{4\pi f_a} a \epsilon^{\mu\nu\lambda\rho} F_{\mu\nu} F_{\lambda\rho}$$

rotation of the CMB polarization:

$$\boxed{\Delta\beta = \frac{C\alpha}{2\pi f_a}\int d\tau \dot{a} = \frac{C\alpha}{2\pi f_a}\left(a(\tau_0) - a(\tau_{rec})\right)}$$

rotation angle max for $m_a < H(\tau_{rec})$ and $m_a > H_0$

Initial value of axion set primordially during inflation.

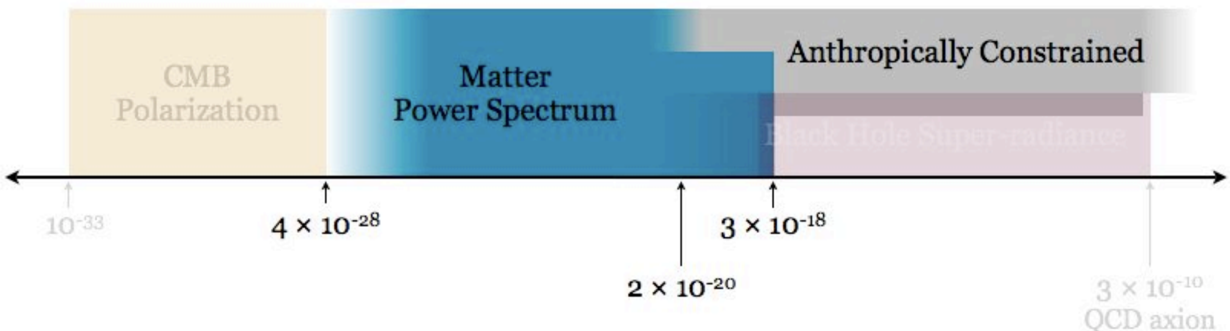
$$\langle a(\tau_{rec}) \rangle \sim \pi f_a / \sqrt{3}$$

Final axion value almost zero now due to Hubble expansion

$$\Delta\beta = \frac{C\sqrt{N}\alpha}{2\pi f_a}(a(\tau_0) - a(\tau_{rec})) = \frac{C\sqrt{N}\alpha}{2\sqrt{3}} \sim few \times 10^{-3}\sqrt{N}$$

transforms CMBR polarization E-mode into B-mode
(parity breaking) BT, EB cross correlations

- constant throughout the sky
- independent of f_a , H_{infl}
- current bound: 0.024 Planck: 10^{-3} CMBPol: 10^{-4}

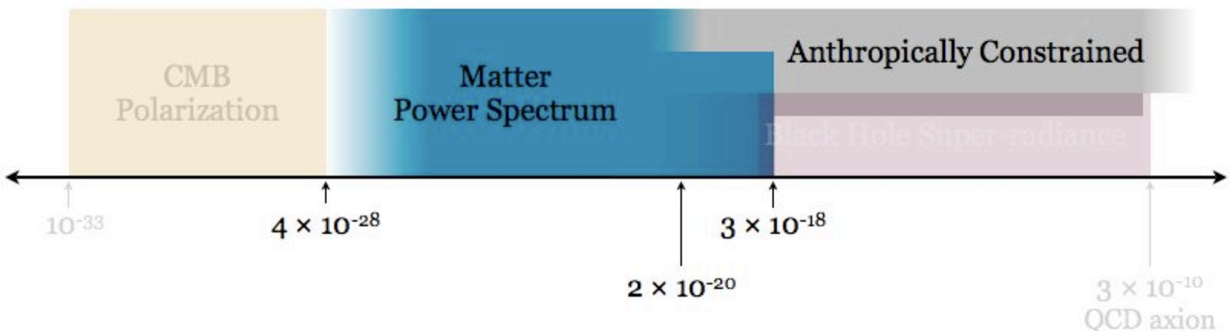


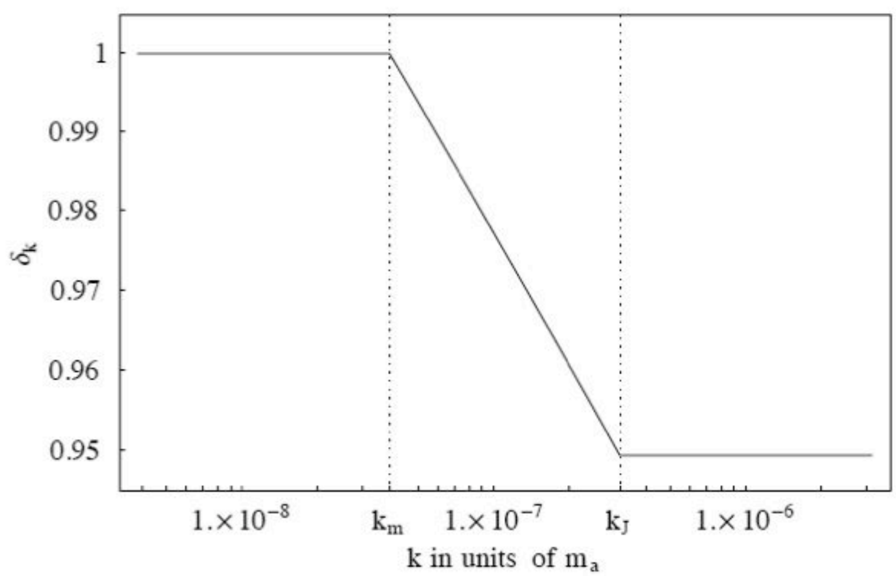
Purely gravitational signature:
presence of steps in the matter power spectrum
if axions are part of DM

Axion DM behaves just like ColdDM (despite being a BEC) except at "small" scales where

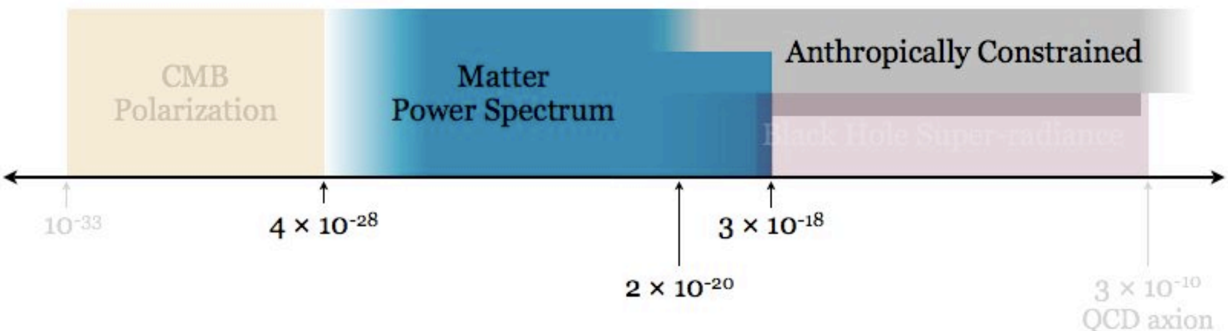
Uncertainty Principle prevents density perturbation growth at

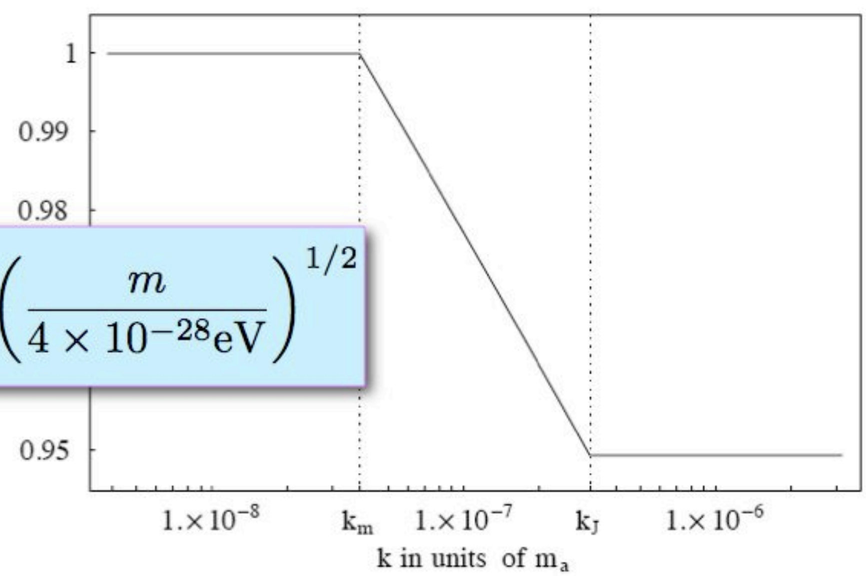
$$\frac{k_J}{a} > \sqrt{Hm}$$





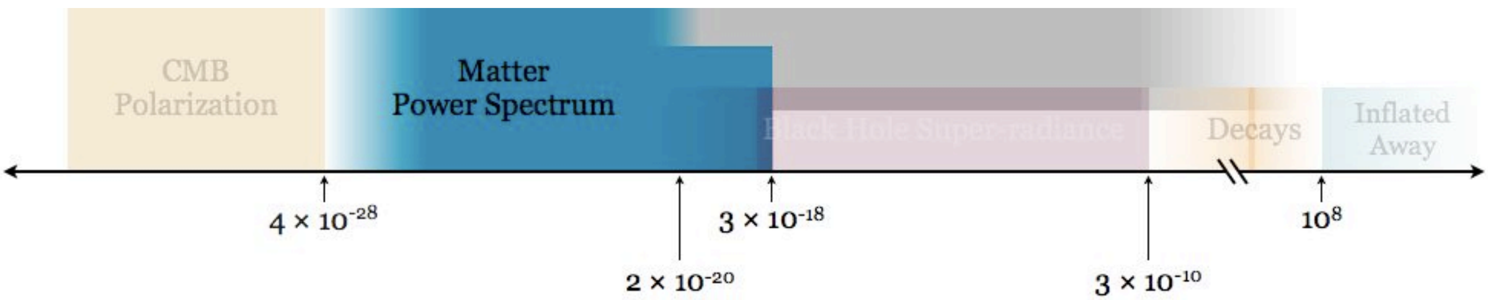
$$k_m \sim (mH_0)^{1/2}(\Omega_m/z_{eq})^{1/4} \qquad\qquad k_J \sim (mH_0)^{1/2}(\Omega_m)^{1/4}$$



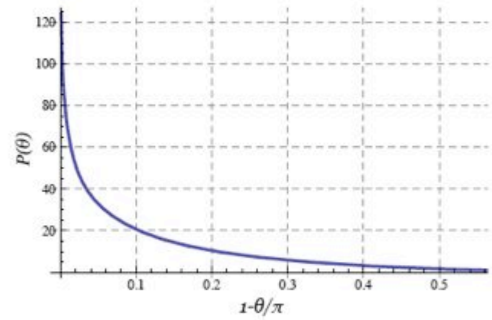


$$k_m = 0.01\text{Mpc}^{-1}\left(\frac{m}{4\times 10^{-28}\text{eV}}\right)^{1/2}$$

step size: $S = \dfrac{\Omega_a}{\Omega_m}\log z_{eq}/z_{obs} \approx 8\dfrac{\Omega_a}{\Omega_m}$ **for typical observation z**



$$\frac{\Omega_a}{\Omega_m} = \frac{f_a^2}{3M_{Pl}^2}\frac{z_m}{z_{eq}}P(\theta_i)$$



Future large-scale structure obs:

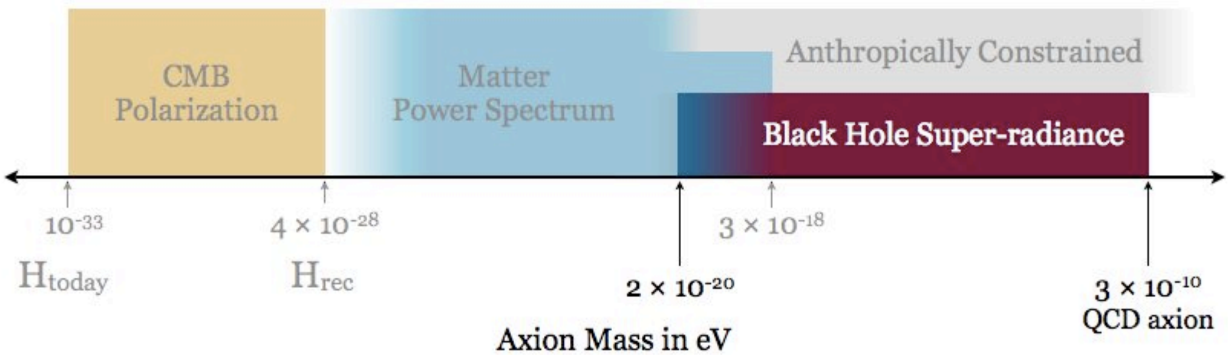
BOSS (SDSS III): S few % at $k \sim 0.1\mathrm{Mpc}^{-1}$ $\quad m_a \sim \mathrm{few} \times 10^{-26}\mathrm{eV}$

21 cm tomography: $k \sim 10^{-2} \div 10^{3}\mathrm{Mpc}^{-1}$ $\quad m_a < 3 \times 10^{-18}\mathrm{eV}$

Note: starting to probe the anthropic region

$S \sim 1$ at $m \approx 1.4 \times 10^{-20}\mathrm{eV}\frac{1}{P(\theta)^2}\left(\frac{3M_{Pl}^2/f_a^2}{10^4}\right)^2$

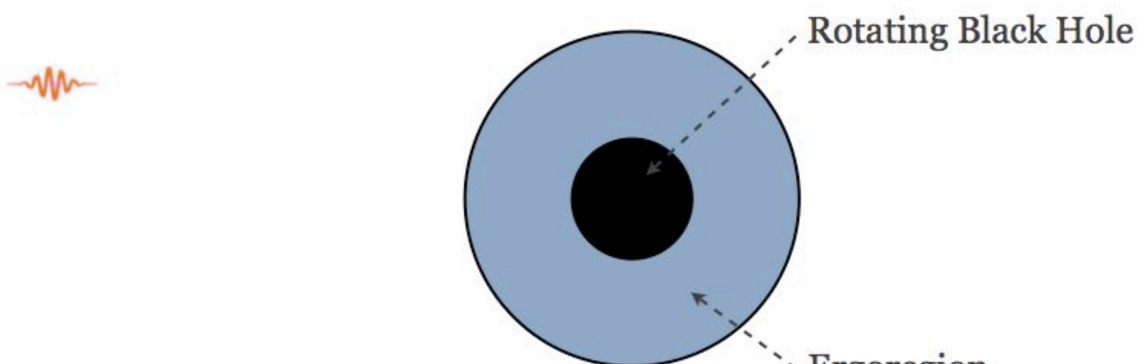
Kerr Black Hole Super-Radiance



Light axions lead to an efficient spin-down of Kerr black holes

Black Hole Superradiance

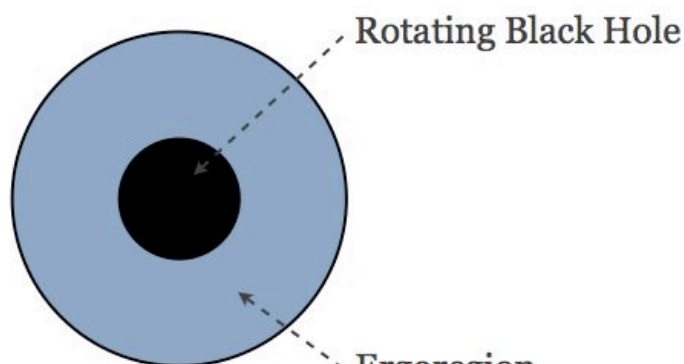
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

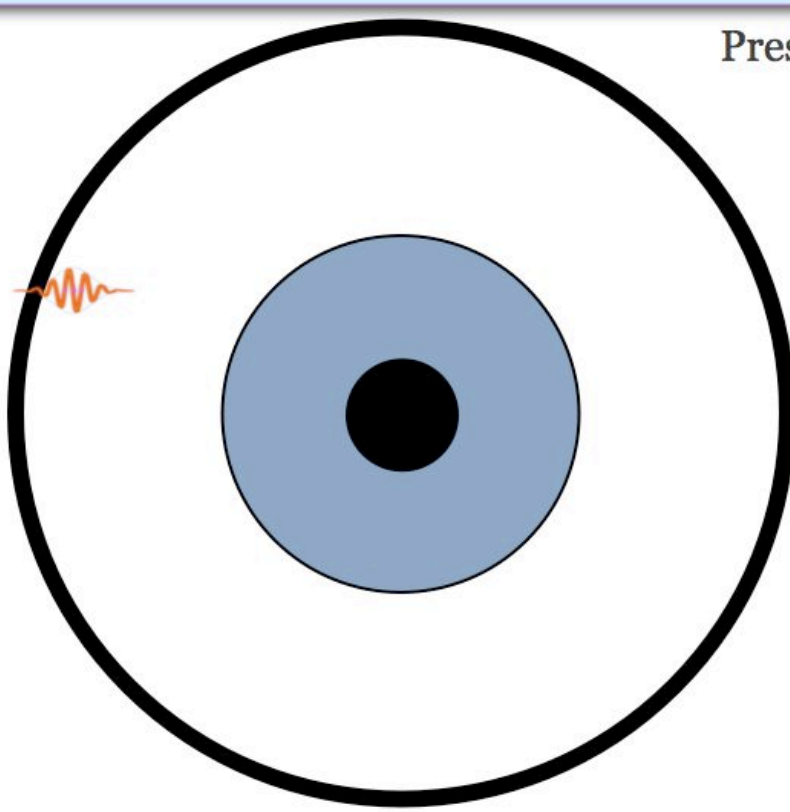
Penrose Process



Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

Press & Teukolsky 1972



Photons reflected back and forth from the black hole
and through the ergoregion

Black Hole Bomb

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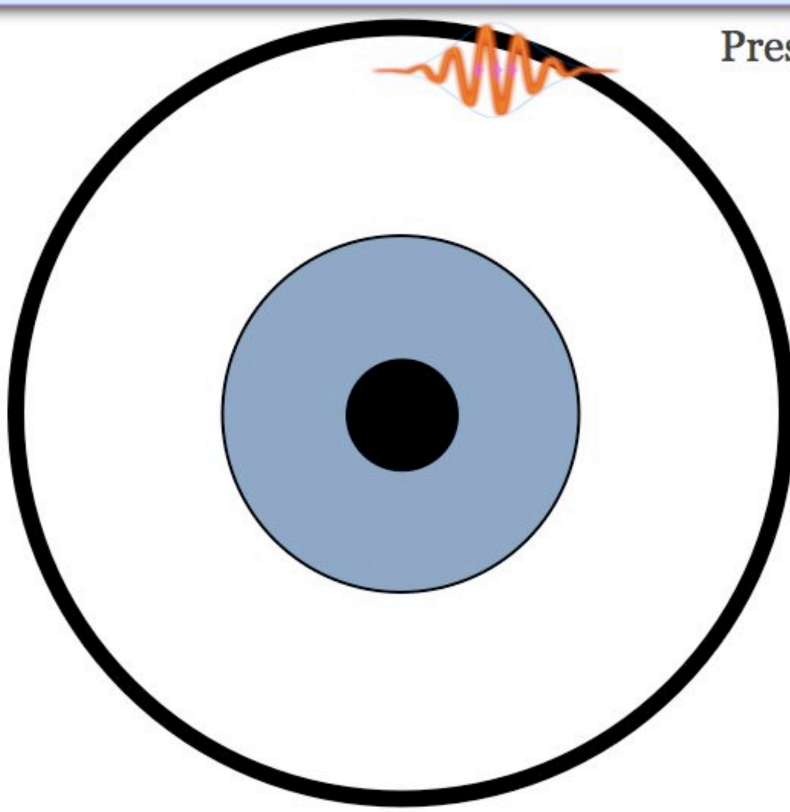

Photons reflected back and forth from the black hole
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Superradiance for a Boson

Penrose Process

Damour et al; Gaina et al.;
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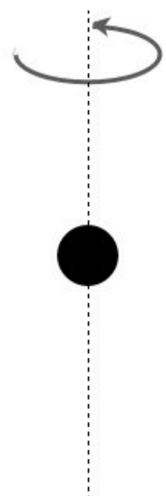

Particle Compton Wavelength comparable to the size of the Black Hole

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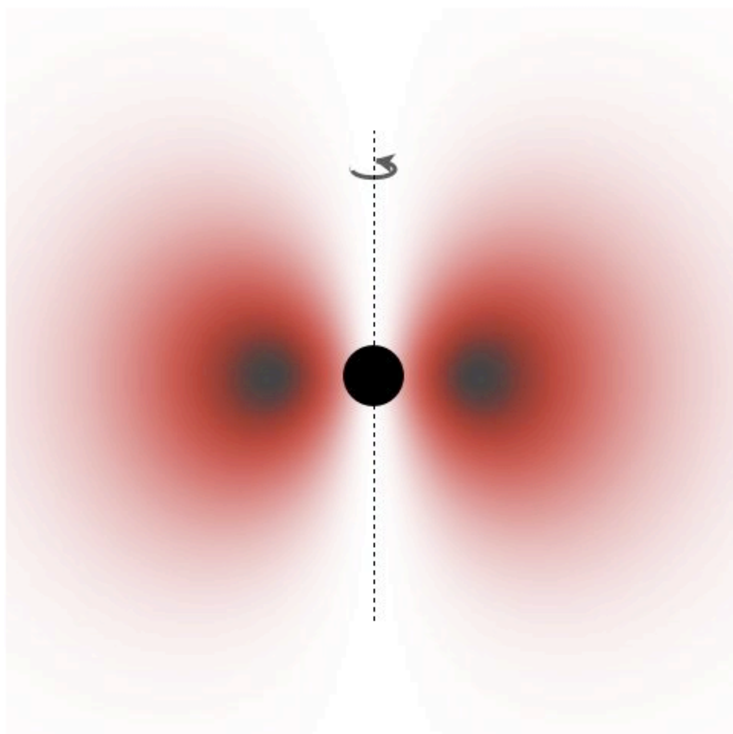
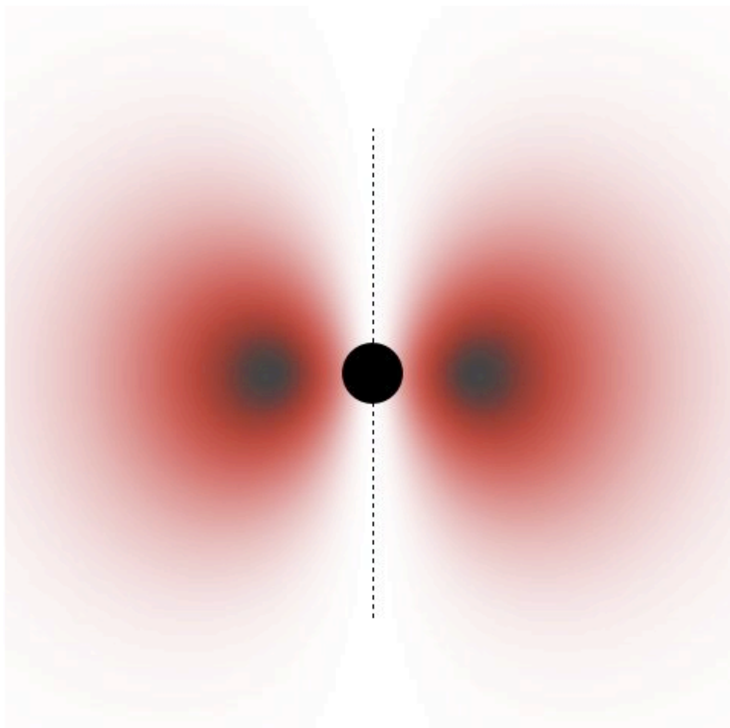


Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

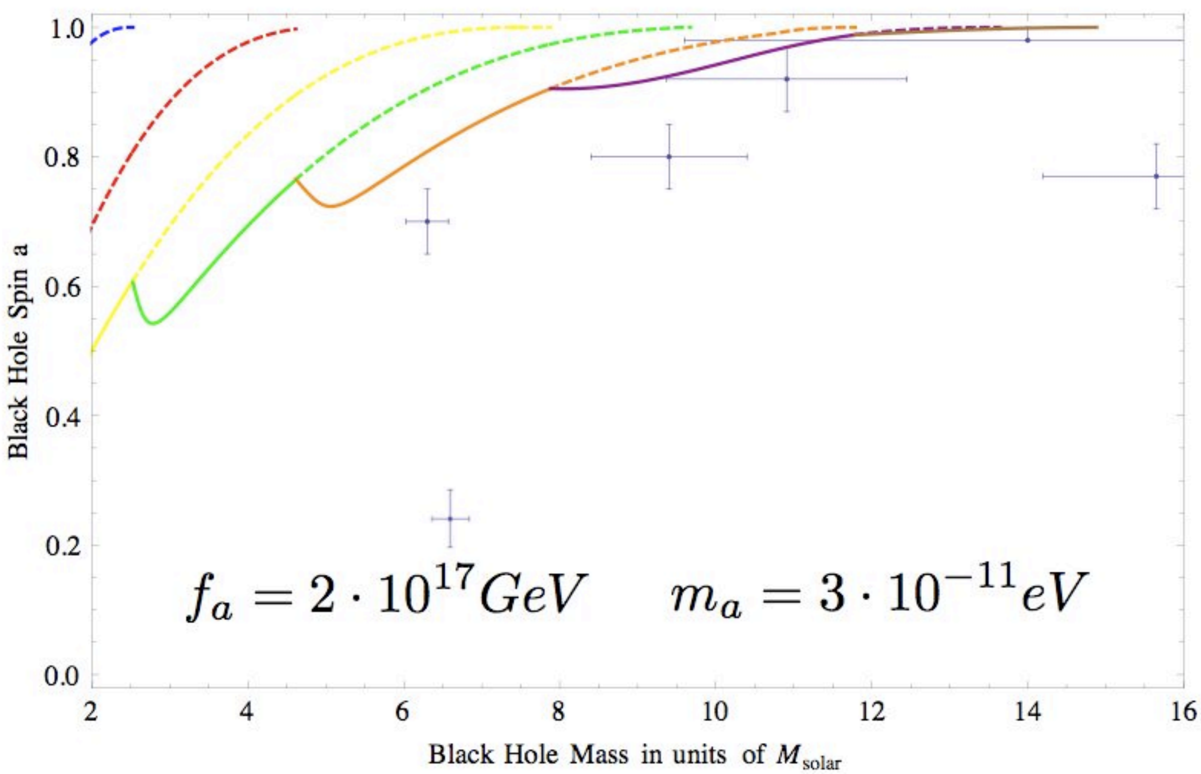


Occupation number ~10^{75}

Relevant Dynamical Processes

- Superradiance
- Gravity wave emission from transitions between levels and annihilation
- Axion self-interactions
- Accretion

Regge trajectories for the QCD Axion



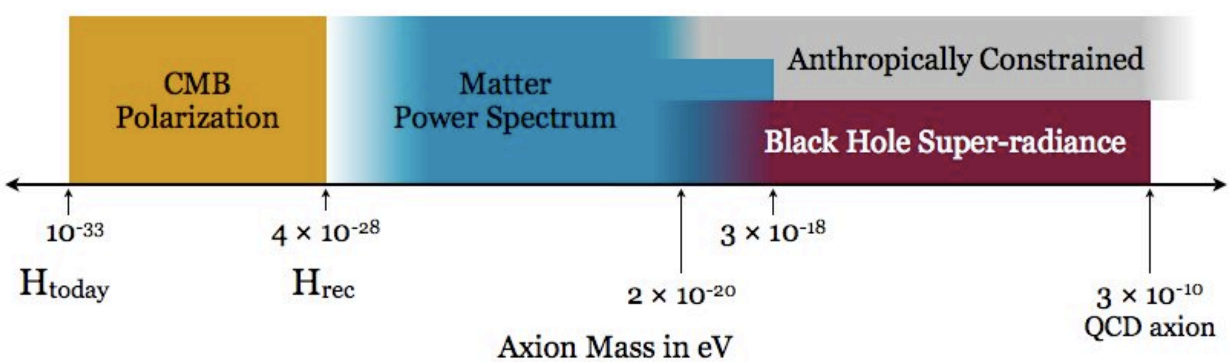
Direct Signals from the Cloud

- Gravity waves from "atomic transitions"
  Advanced LIGO frequency range for the QCD axion
- Bosenova
  Gamma rays for the QCD axion
- Axion cloud modifies the metric around Black Holes
  Precision measurements with future low frequency gravity wave detectors
- *Photon conversion of axions from the cloud in the magnetic field*
  Radio wave signals

In the next decade cosmo and astro observations will be exploring 23 orders of magnitude in energy

Taking strong CP and properties of axions in string theory seriously, suggests this is not a desert, and we have a chance to be observationally exploring the topology of the compactification manifold

astrophysical BHs serve as a probe of string theory



Photi- & Photini-verse

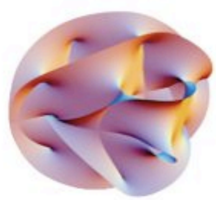
Many U(1)'s can also arise

RR antisymmetric forms

$C_4 \quad (IIB)$

$C_3 \quad (IIA)$

$\xrightarrow{\text{compactification}}$



many (few10's-100's)
KK zero modes from topology (cohomologies)

e.g., $X_i^\mu = \int_{\Sigma_i^3} C_4$

Inherit gauge symmetry from underlying 10d abelian gauge symmetry of RR field

Important property of RR U(1)'s: no light charged states

due to fact that arise from multi-index fields that naturally couple to D-branes (not point particles)

couple to us via kinetic mixing with hypercharge

Important property of RR U(1)'s: no light charged states

due to fact that arise from multi-index fields that naturally couple to D-branes (not point particles)

couple to us via kinetic mixing with hypercharge

No signals from photons

BUT the photini are coupled

the difference is that they are massive from SUSY breaking

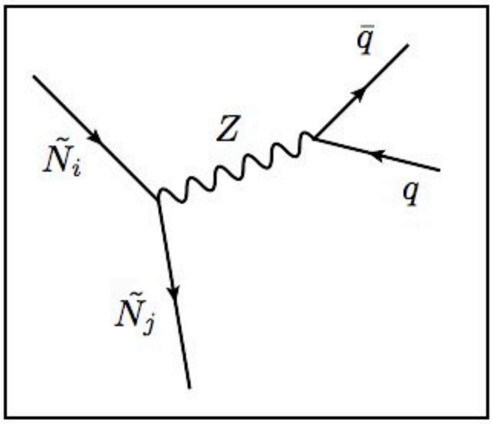
$$\delta\mathcal{L} = iZ_{ij}\lambda_i^\dagger\ \partial\!\!\!/\lambda_j + m_{ij}\lambda_i\lambda_j$$

and both kinetic and mass-mixing with bino are possible

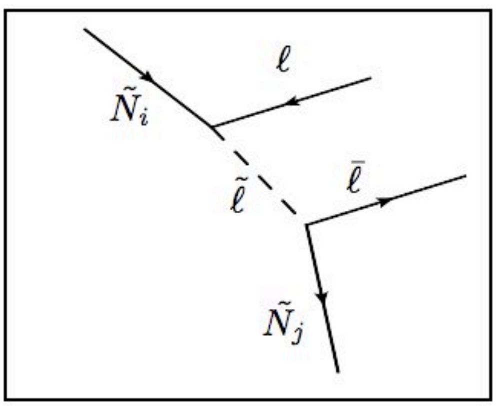
The MSSM neutralino sector gets enlarged

$$\lambda_I = (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u, \tilde{\gamma}_1, ..., \tilde{\gamma}_n)$$

Inter-photini decays



$$\Gamma^{Z^*}(\tilde{N}_i \to \tilde{N}_j + f\bar{f}) \simeq$$
$$\frac{\alpha_W^2 \times \text{MSSM mixings}}{192\pi^3} (\epsilon_{eff,ij})^4 \left(\frac{M_i M_j}{M_{\tilde{B}}^2}\right)^2 \frac{(\delta m)^5}{m_Z^4}$$



$$\Gamma^{\tilde{l}}(\tilde{N}_i \to \tilde{N}_j + f\bar{f}) \simeq$$
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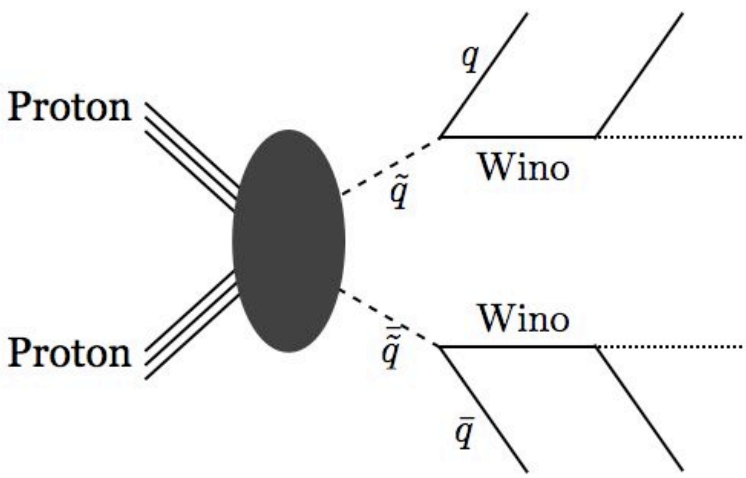
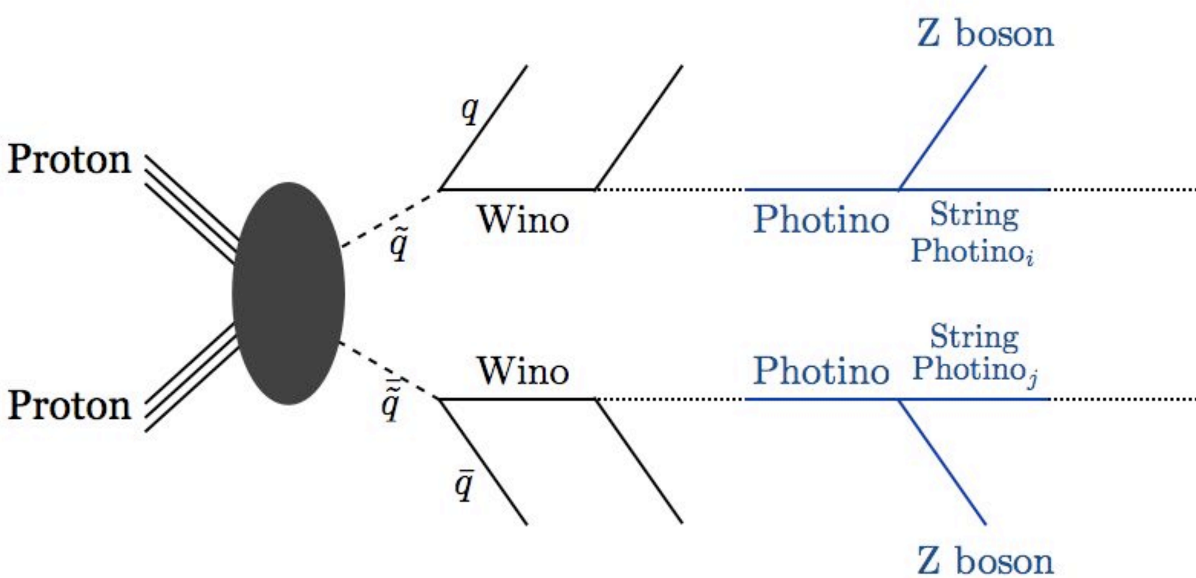
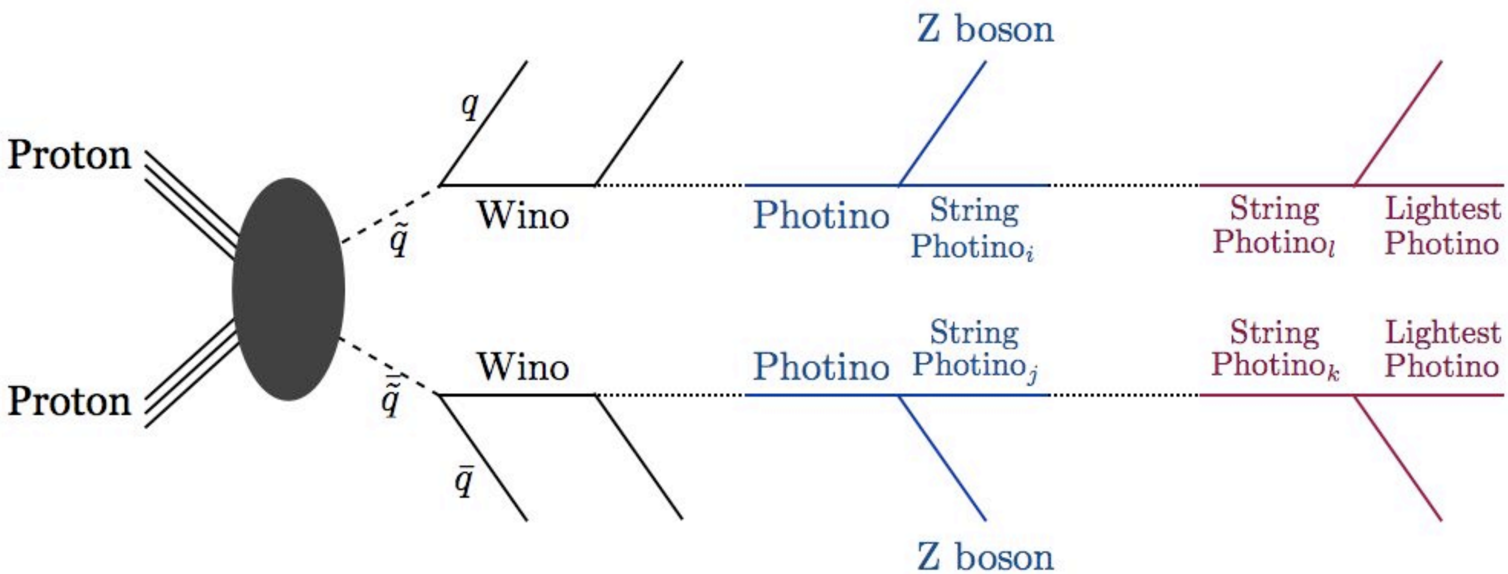
Cascade decays



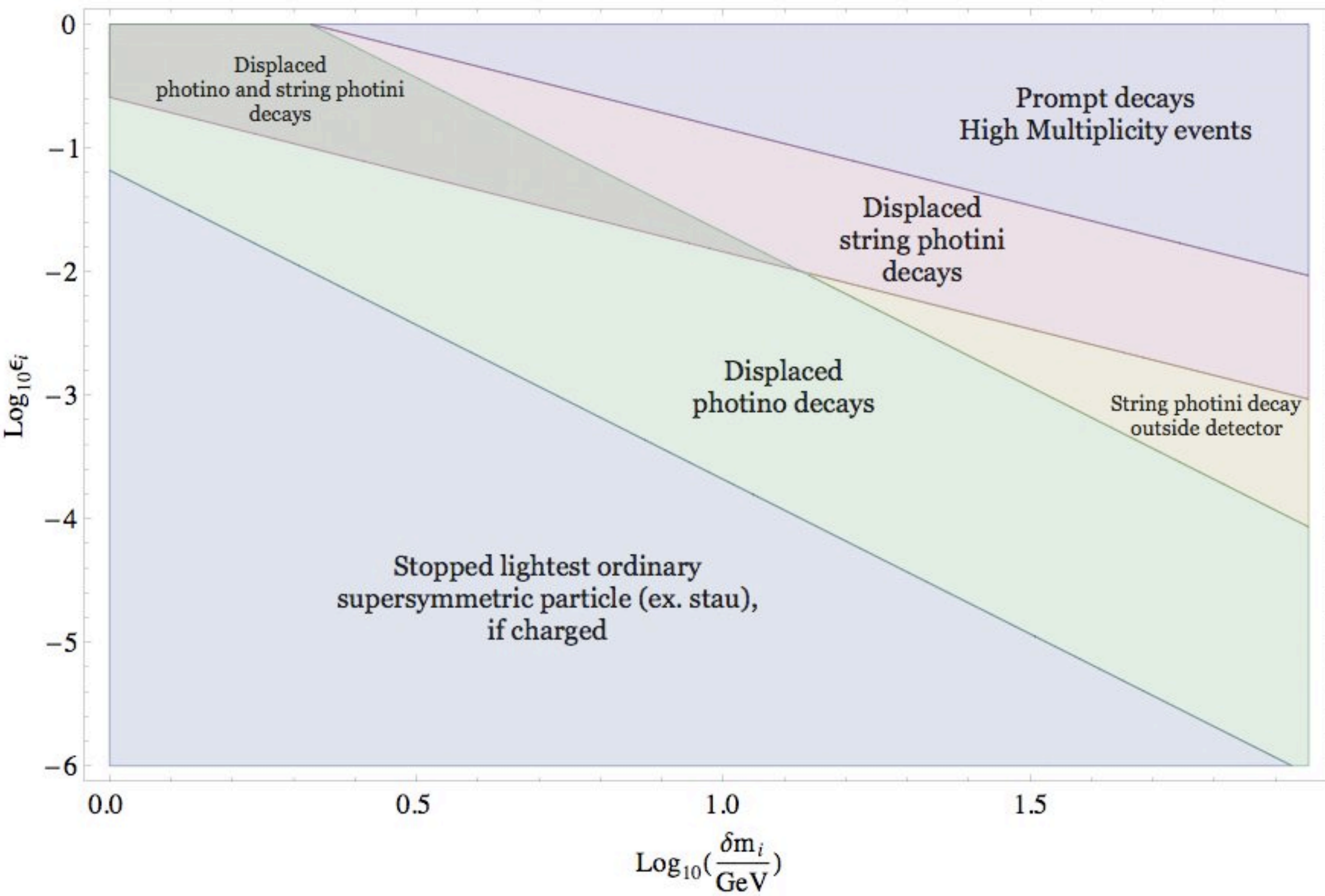
Cascade decays



Cascade decays



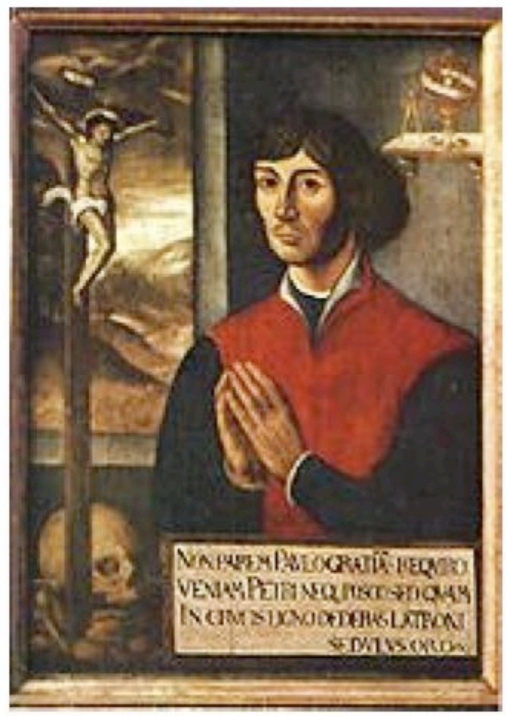
Photini Signatures at the LHC



Discovery through reconstruction of masses and mass splittings

Dynamics *vs* Anthropics

Claudius Ptolemaeus



Nicolaus Copernicus

Minimalism *vs* Plenitude

William of Ockham

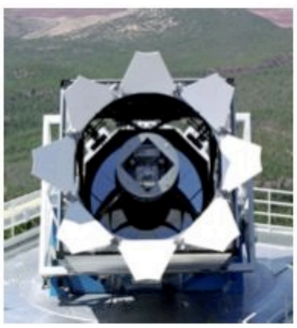
"entia non sunt multiplicanda praeter necessitatem"

entities must not be multiplied beyond necessity

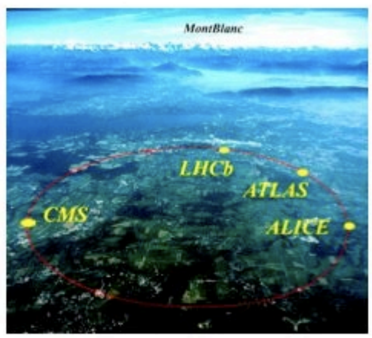
Gottfried Wilhelm Leibniz

" This best of all possible worlds will contain all possibilities, with our finite experience of eternity giving no reason to dispute nature's perfection."

DATA will tell



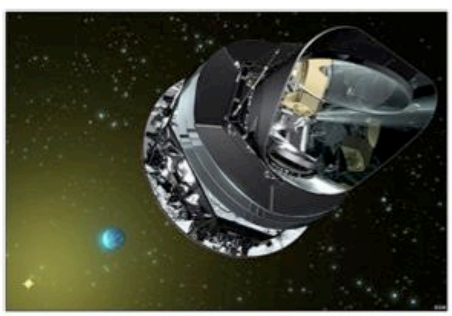
BOSS



LHC

Advanced LIGO

IXO



Planck

Atom Interferometry